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A CFD based approach for determination of ammonia concentration profile and flux from poultry houses with natural ventilation

Una aproximación basada en CFD para determinar perfil de concentración y flujo de amoniaco en galpones avícolas con ventilación natural

doi: 10.15446/rfna.v69n1.54750

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ABSTRACT

Key words:
Computational Fluid Dynamics
Natural ventilation
Broiler chickens
Ammonia
Tropical climates

The understanding of concentration and emissions distribution of gases such as ammonia (NH_3) in agricultural installations is of growing importance due to its effect on health and productivity of animals and workers. The objective of this study was to use validated Computational Fluid Dynamics (CFD) model as a tool to predict NH_3 concentration distribution and mass fluxes in a non-insulated broiler chicken installation with natural ventilation, typically found in subtropical and tropical countries. Results from this study indicated that simulation with CFD can be used to predict NH_3 concentration distribution and mass flux inside similar installations with incident winds from different directions of entrance at the lateral opening of the installation. The most direct application of the proposed model would be to help improving the existing buildings and also to help in the conception of new ones, and may also apply the model to help in the development of NH_3 emission inventories.

RESUMEN

Palabras claves:
Dinámica de Fluidos Computacionales
Ventilación natural
Pollos de engorde
Amoniaco
Climas tropicales

El entendimiento de la concentración y distribución de las emisiones de gases como el amoníaco (NH_3) en instalaciones agrícolas es cada vez más importante debido a su efecto sobre la salud y la productividad de los animales y de los trabajadores. El objetivo de este estudio fue utilizar un modelo validado en Dinámica de Fluidos Computacional (CFD) como herramienta para predecir la distribución de la concentración y flujos de NH_3 en una instalación de pollos de engorde sin aislamiento térmico y con ventilación natural, típicamente encontrados en países tropicales y subtropicales. Los resultados de este estudio indicaron que la simulación con CFD se puede utilizar para predecir la distribución de concentraciones y flujo de NH_3 dentro de instalaciones similares con vientos incidentes con diferentes direcciones de entrada en la abertura lateral de la instalación. La aplicación más directa del modelo propuesto sería ayudar a la mejora de las instalaciones existentes y también para la concepción de nuevas, como también se puede aplicar el modelo para ayudar en el desarrollo de inventarios de emisiones de NH_3.

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Received: March 6, 2015; Accepted: September 15, 2015
Rev. Fac. Nac. Agron. Medellín 69(1): 7825-7834. 2016 ISSN 0304-2847 / e-ISSN 2248-7026

The improvement of air quality within livestock buildings as well as the reduction of gaseous emissions from them has been a goal of much research carried out throughout the world. In this context, air quality is the capability to maintain appropriate air change rates, temperature and humidity, gas concentration such as ammonia (NH_3), methane (CH_4), within an optimum range for the animal species being housed. Therefore, the internal environment is an important factor in the intensive production of livestock such as poultry, influencing animals' metabolism, its capacity to dissipate heat and water vapor and as a consequence, is intently linked to the susceptibility to respiratory diseases (Macari *et al*., 2001). Moreover, the gases generated by decomposition of manure and dust liberated by bedding within the building contribute to the polluting of the outdoor air as well as surrounding ecosystems.

Regions with tropical and subtropical climates such as Brazil are populated with intensive broiler chicken production facilities that utilize open curtain-sided sidewalls for ventilation to exploit favorable wind conditions and use assisted mechanical ventilation when this is not possible. However, owing to the openness of these buildings in windy conditions there is often significant lack of precision in ventilation control within because wind direction and velocity has a big impact on ventilation uniformity.

The quality of air within facility and its vicinity can not only affect the health of confined animals but also of workers which spend 4 to 8 hours a day in this environment. Given that birds are now raised under high densities, the thermal comfort of these animals is easily compromised. It is recognized that for intensive poultry production to be sustainable in tropical and subtropical countries, there must be significant improvement of housing facilities to improve poultry performance, reduce production costs and reduce environmental impacts (Osorio *et al.,* 2013).

Ammonia volatilization from broiler litter is also one form of nitrogen loss from confined animal operations, which negatively impacts the environment while reducing litter fertility potential (Ndegwa *et al*., 2008). NH_3 is the product resulting from the enzymatic or biological degradation of uric acid present in the litter, in a five steps process (Singh *et al.,* 2009) and has been largely regarded as one of the causes of acid rains and excess deposition of nitrogen in ecosystems that are sensible to this nutrient. The consequences of excess nitrogen deposition in ecosystems can be the modification of such ecosystems (Demmers *et al*., 1998), and the occurrence of environmental stress situations such as the eutrophization of lakes and rivers and soil acidification (Monteny *et al*., 1998). Further, the effect of concentrations and exposure times to NH_3 on the health and performance of animals and workers is notable, which illustrates the importance of understanding distribution of ammonia concentration inside animal production installations. Hence, these have been regarded as important reasons that motivate researchers around the world to know the magnitude of ammonia fluxes from the different sectors of an animal production industry.

One of the first steps towards improving livestock facilities in sub-tropical/tropical countries is to develop appropriate approaches for monitoring and modeling the internal environment. There are various methods to determine distribution of these NH_3 concentrations and mass flux at any given moment where the most utilized are systems of continuous monitoring such as the Portable Monitoring Units (PMUs) developed by (Gates *et al.,* 2005) and used in the studies performed by (Pecegueiro *et al.,* 2007; Blunden *et al.,* 2008; Sommer *et al.,* 2009), as well as the tracer gas method used by (Dore *et al.,* 2004; Scholtens *et al*., 2004).

These methods offer good precision, however require continuous or semi-continuous monitoring of NH_3 concentrations and ventilation rate , and the prediction and correlation of the trends only possible via statistical analysis of the collected data. However, for naturally ventilated structures the calculation of the gaseous emissions is complicated by the variability of the wind environment, meaning approaches where ventilation rates can be physically modeled or monitored in such buildings are necessary. Owing to the capacity of Computational Fluid Dynamics (CFD) to evaluate the behavior of climatic variables inside both vegetation and animal structures, it presents a useful modeling technique to combine with concentration measurements for naturally ventilated livestock buildings (Norton *et al*., 2009, 2010; Reynolds *et al.,* 2009).

However, despite its applicability, the majority of studies developed with CFD are for analysis of pollutant distributions, such as NH_3, within mechanically ventilated structures for cattle and hogs which are typical of countries with temperate climates (especially in Europe and North America). However, there are known studies are applied to highly open poultry installations with natural ventilation, non-insulated and typical of tropical and subtropical countries.

The objective of this study was to develop and validate a CFD model in order to (a) evaluate the ventilation efficiency and (b) analyze the distribution of NH_3 concentrations and the magnitude of NH_3 fluxes in a naturally ventilated, non-insulated broiler chicken house. This study provides the starting point for seeking to obtain a low cost, efficient and widely applicable tool which would allow for real time prediction of concentration and emissions of this type of pollutant from structures common to tropical and subtropical countries.

MATERIALS AND METHODS

Description of the experimental site and barn

The broiler house (Figure 1) that was modeled and simulated is located in the municipality of Viçosa, Minas Gerais State, Brazil. The building design represents a typical construction within a vertically integrated system of producers that connected to a local poultry products processing facility within Viçosa. The commercial broiler facility used in this investigation housed 14000 male Cobb chickens, with a stocking density of 14 birds m^{-2}. The barn is not thermally insulated, and most of the time operated using natural ventilation. Bedding was composed of fresh coffee hulls.

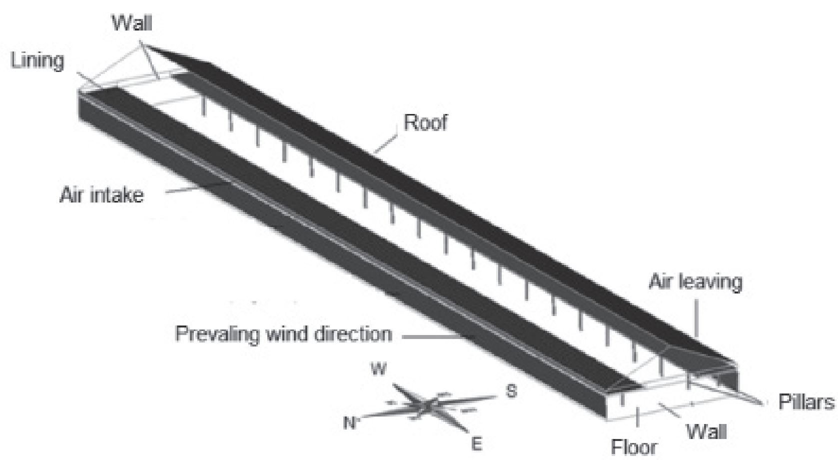

Figure 1. Diagram of the modeled and simulated installation.

Experimental data acquisition

Collection of experimental data was done during three consecutive days of each distinct week in the life of the birds, namely during the following periods: 22-28, 29-35 and 36-48 days of the productive cycle. The experiment was performed while the poultry house was maintained open and with natural ventilation.

The *1-Wire™* technology was used to monitor temperature inside the installation at 1-s intervals, using 36 sensors distributed inside the installation and located at three different heights above the floor (0.2, 1.2 and 2.2 m). The software STRADA (Rocha *et al.,* 2008) was adopted for experimental data acquisition and control. A DS9490R USB adaptor was connected to a laptop computer with an *Intel Pentium®* 100 Mhz processor and 64 Mb of RAM for data transfer from the *1-Wire™* network.

Aerial NH_3 concentration data were monitored by means of a handheld sensor (BW electrochemical detector, "Gasalert Extreme NH_3 Detector"), with a measurement range from 0 – 100 ppm, operating temperature between -4 and +40 °C and relative humidity (RH) from 15% to 90% and with an accuracy of $\pm$ 2%. Concentration data was sequentially collected at each of the 36 points, data acquisition was manually done every hour interval. Air speed (m s^{-1}) was measured with a digital wind gage (Testo 425) inside the experimental barn, ranging between 0 - 20 m s^{-1}, precision of 0.1 ºC ± 0.5%, accuracy of ± 1% (pressure) and 2.5% (m s^{-1}). Air velocity data was collected at every 1-s intervals in the same position that was measured the air temperature. External air temperature and air relative humidity (RH) values were registered with a model HO8, HOBO datalogger, installed in a meteorological station located near the poultry house at 1.5 m off the ground, with resolution of 0.5 °C 1% and collecting data once at every second. Temperatures of the roof and lining were measured with a TD95 model ICEL infrared thermometer, ranging between -20 and +270 ºC, with resolution of 1 °C and accuracy of ± 2%.

Determination of the ammonia mass flux from the building

The Saraz Method for Determination of Ammonia emissions (SMDAE) proposed by Osorio et al. (2013), consists of a passive diffusion collector, based on a polyurethane sponge whose function is to absorb the gaseous NH_3 emitted by the building. The SMDAE, was used to measure the NH_3 emitted by the open, naturally ventilated studied poultry house, using the passive flux chamber (PFC), forming a homogeneous mesh organized at the lateral opening of the building in the opposite direction of the predominant wind (i.e. downwind side of building). At these equidistant points, twelve (12) PFCs were positioned along the lateral wall, near the air outlets on lines A, B, C and D, at heights of 0.80, 1.50 and 2.20 m from the floor (Figure 2). The NH_3 concentration captured by the sponge and the mass flux was also obtained using the methodology proposed by Osorio *et al.* (2014) (equation 1).

$$SMDAE(g\ NH_3 M^{-2} S^{-1}) = \frac{NH_3}{At} \quad (1)$$

Where SMDAE is the ammonia flux (g NH_3 m^{-2} s^{-1}), NH_3 is the ammonia mass (g NH_3), A is the sponge area (m^2) and t is the exposure time of the sponge (s).

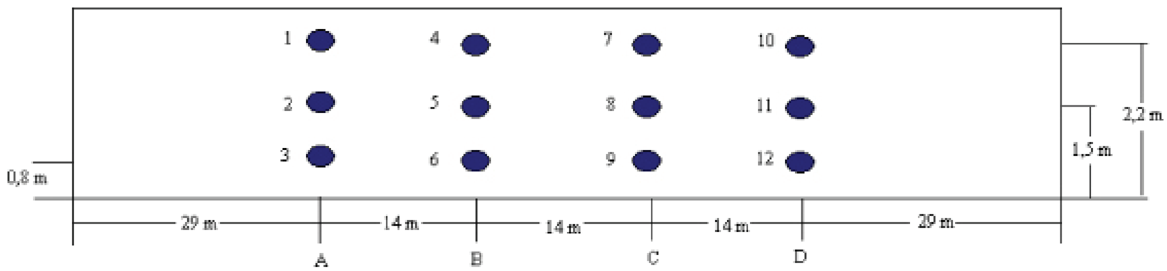

Figure 2. View of the downwind side of the studied poultry house showing the position of the passive flux chambers (PFCs) on the lateral wall

Numerical formulation

This research involved numerical simulation using CFD modelling to predict results with available experimental data. ANSYS CFX® was employed to implement and simulate the proposed model.

Computational domain

A three-dimensional (3D) computational domain was developed for the simulations (Figure 3). The computational mesh was first generated with different refinement levels using the software ANSYS ICEM - CFX Mesh®. Different types of tetrahedral and quadratic meshes were generated aiming at optimum results, but the best results were obtained using tetrahedral mesh. The constant values input used in the simulations, corresponded to the most critical conditions during the day, where the NH_3 flux and concentrations were higher, are shown in Table 1.

Computational modeling

Air flow rates were associated with turbulent flows and combined with heat transfer rates, generating a complex system of coupled equations difficult to resolve. Therefore, the Navier-Stokes and energy equations for determining air velocity, temperature and pressure were internally solved by the CFD package through the finite volumes technique. The model for non-isothermal fluid flow is described by the equations of mass, continuity,

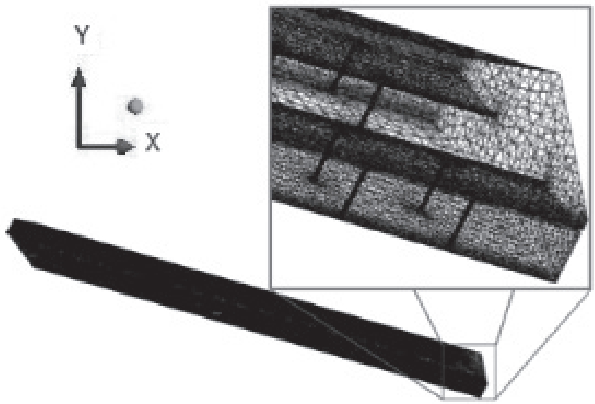

Figure 3. Refinement detail of the computational tetrahedral mesh.

Table 1. Constant input used in the simulation

Location	Variable	Value
Inlet	Average air speed Air temperature	0.76 m s^{-1} 22.2 °C
Outlet	Manometric pressure Average temperature	0 Pa 23.0 °C
Lining	Average temperature	24.6 °C
Roof	Average temperature	22.5 °C
Floor	Average temperature	23.5 ° C

energy and transport of any gaseous species, (equations 2 – 5) (Kim *et al*., 2008).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{2}$$

$$\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho UU) = \nabla p + \left[\mu_\tau (\nabla U + \nabla U^T \right] + F_i \tag{3}$$

$$\frac{\partial(C_p T)}{\partial t} + \nabla \cdot (-k\nabla T + \rho C_p TU) = 0 \tag{4}$$

$$\frac{\partial C_A}{\partial t} + \vec{m} \cdot \nabla C_A = \nabla \cdot (D \nabla C_A) \tag{5}$$

Where C_p is the specific heat (W kg^{-1} K^{-1}), C_A is the concentration of species A in the gas (g m^{-3}), K is the thermal conductivity (W $m^{-1}K^{-1}$), $\overline{m}$ is the velocity component (m s^{-1}), P is the Pressure (N m^{-2}), U is the velocity vector, ρ density (kg m^{-3}), μ_τ is the dynamic fluid viscosity (kg $m^{-1}s^{-1}$) and T the transposition tensor.

Turbulent flow was modeled using the k-ε standard model, which adds an extra stress (Reynolds stress) in viscosity (μ_τ). This model relates the turbulent kinetic energy (k) and dissipation of turbulent kinetic energy (ε) (Lee *et al.,* 2007). The F_i term in the equation 3, is the Boussinesq model that was used to take into account the gravity effect, i.e. the buoyancy force due to air density differences that are included in the momentum equation as a linear function of the local temperature differences (Pedersen *et al.,* 2000).

Boundary conditions

The following criteria were made:

1. Barn floor was almost completely covered by the animals, implicating in a semi-uniform heat flux from the birds.
2. The heat flux generated by the birds (Q_{ct}), (Equation 6) was found as a function of environmental temperature

of the building and the animal body weight. The heat flux generated by the birds was estimated using the following expression (Pedersen *et al.,* 2000).

$$Q_{ct} = 10 \cdot m_{kg}^{\ 0.5} \cdot \left(4 \cdot 10^{-5} \cdot (20 - T)^3 + 1\right) \qquad (6)$$

3. The effect of the barn columns on heat and mass transfer processes were considered.

4. The SMDAE method was used to experimentally determine the NH_3 flux (N''_A) from the bedding, by capturing the total ammonia nitrogen (TAN) that was volatilized. For representation of the mass convection, a boundary limit model (equation 7) was used for concentration of a chemical species on a flat surface, where N''_A is the NH_3 flux (g m^{-2} s^{-1}) and h_m the mass diffusion coefficient. This coefficient is a function of the Reynold's number (Re) and the Schmidt number (Sc); Mass flux by convection is determined as (Incropera, 1999):

$$N''_A = h_m (C_{A,S} - C_{A,\infty}) \qquad (7)$$

Validation of the model

The results obtained from the simulations were verified and compared with the corresponding data in the mesh test and such as NH_3 concentration and mass flux obtained experimentally using a non-parametric one-way analysis of variance (ANOVA, Kruskal-Wallis test), with a sample size of 36 experimental measurements.

RESULTS AND DISCUSSION

Test of meshes and validation of the computational model

The tested meshes were composed of 197325 nodes and 191215 elements (mesh 1), as compared with a more refined mesh composed of 157219 nodes and 189004 elements (mesh 2). The two types of tetrahedral meshes that were developed and no significant differences were found (P=0.219), for NH_3 concentration, due to their refinement levels, therefore mesh 2 was selected, to perform the simulations.

Analysis of NH_3 concentration profiles throughout the building

The experimental values of NH_3 concentration did not differ significantly from those obtained from the simulations (P=0.175).

Figure 4 presents the typical NH_3 concentration profile inside the poultry house obtained by the developed model. As expected, NH_3 concentrations were greater when there was interference of the pillars, as well as near the walls. A reduction of wind speed in the regions of the walls and pillars might be what caused greater NH_3 concentrations at the height of the birds, especially where winds exit the installation. This phenomenon was also verified in the field. Concentrations of NH_3 at the height of a working person (1.5 m) inside the installation were less than 1 ppm, suggesting that during the period in which the installation

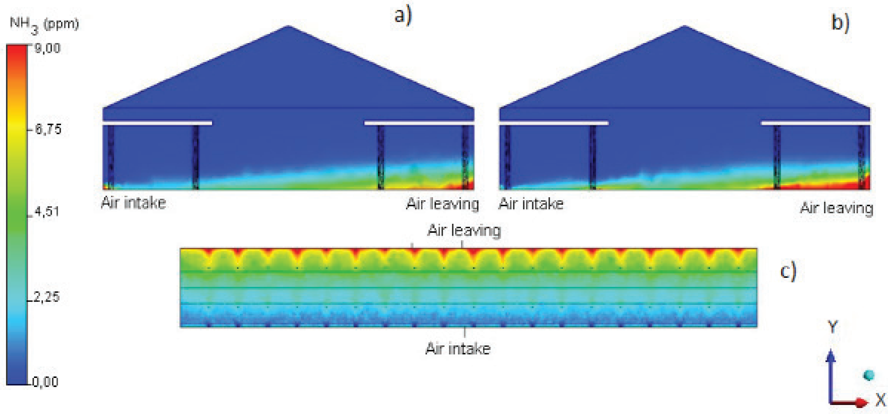

Figure 4. Typical concentrations of NH_3 inside the installation: (a) effect with pillars; (b) effect without pillars at the center of the building; (c) horizontal plane at the height of the birds.

remains open there is no significant accumulation of gas inside the building since all NH_3 generated is emitted by the lateral openings. These results coincide with those encountered in other studies that used other methodologies such as those performed by (Dore *et al*., 2004; Pecegueiro *et al*., 2007; Sommer *et al*., 2009).

Despite the maximum NH_3 concentrations registered in the experimental time at conditions of natural ventilation, they did not surpass recommendation of the National Institute for Occupational Safety and Health (NIOSH) which is 25 ppm for an exposure time of 8 hours. At the lateral openings NH_3 concentrations were observed on the order 15 ppm at the height of the birds, which directly influences emissions generated by the installation. The obtained outcome was already expected, since poultry barns that are naturally ventilated generally usually present low NH_3 concentrations, what reinforces the fact that air quality inside these kind of buildings is usually not detrimental to animal welfare.

Analysis of building ventilation efficiency

It was observed that when the winds entered in a direction perpendicular to the installation, there was a reduction in speed due to presence of the columns inside the installation, however for the majority of the building there was good uniformity of wind speed distribution. At the height of the birds (0.20 m) a reduction in wind speed of approximately 20% was also observed due to the direct effect of the outer walls and pillars along the perimeter of the installation. This effect is not desired in conditions of extreme heat and does not favor good thermal comfort conditions (Figure 5), and agrees to what was encountered in studies performed by Norton *et al*. (2009, 2010) and Osorio *et al*. (2014). Due to the low distribution uniformity of winds, low wind speeds are observed at the extremities of the installation, which may generate greater gaseous accumulations in these sectors as shown in Figure 4.

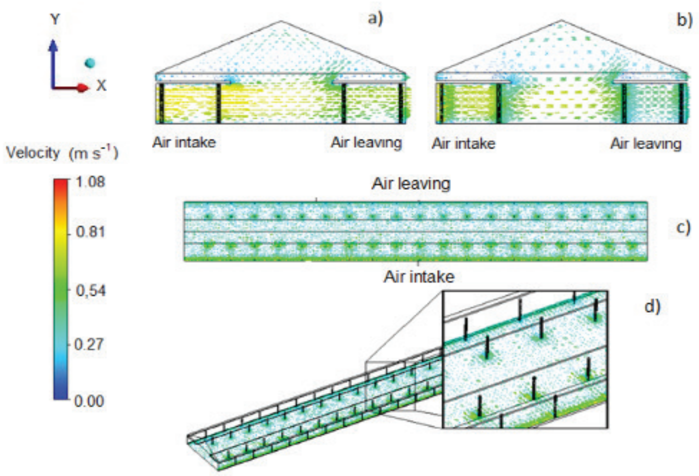

Figure 5. Velocity vectors inside the building with incident wind entrance of 90°: (a) effect with columns inside the building; (b) effect without columns at the center of the building; (c) plane at the height of the birds (0.20 m); (d) magnification of the velocity vectors.

Analysis of NH_3 flux from the building

The NH_3 fluxes emitted from the lateral openings of the building observed in the developed CFD model were compatible with the ranges of the values found by other studies and with the experimental data obtained by Osorio *et al*. (2014), also using the SMDAE methodology as is shown in the Figure 6 in each one of 12 points in the lateral wall (Figure 2). However, the locations where the agreement between methods was poor, are probably due to the fact that the adopted turbulence model is not limited by the assumptions of eddy viscosity.

From Figure 7 one can see the typical NH_3 flux distribution inside and outside of the poultry house. The obtained NH_3 flux or emission data from poultry houses with natural ventilation usually presented lower values (from 10^{-7} to 10^{-4} g NH_3 m^{-2} s^{-1} or between 0.09 – 0.35 g NH_3 d^{-1} per bird), as compared

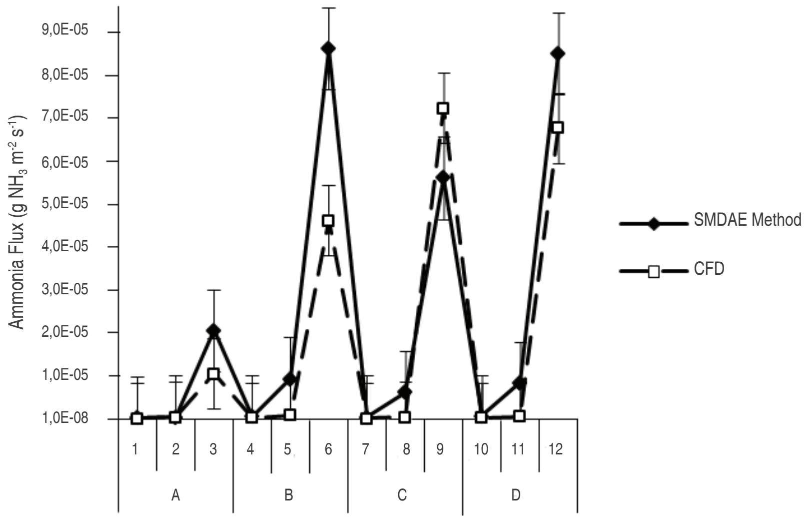

Figure 6. Comparison between NH_3 fluxes obtained experimentally with the SMDAE method and simulated with CFD at different points at the lateral wall.

to the generated from type tunnel mechanically ventilated or other negative pressure broiler house as reported by Hayes *et al*. (2006) (0.16 – 0.50 g NH_3 d^{-1} per bird), by Gates *et al*. (2008) (0.80 – 2.50 g NH_3 d^{-1} per bird) and by Mendes *et al.* (2014) (0.22 – 0.42 g NH_3 d^{-1} per bird) and others, which could present higher fluxes during only the first minutes after that the lateral curtains of the facility are open, when NH_3 concentrations are higher.

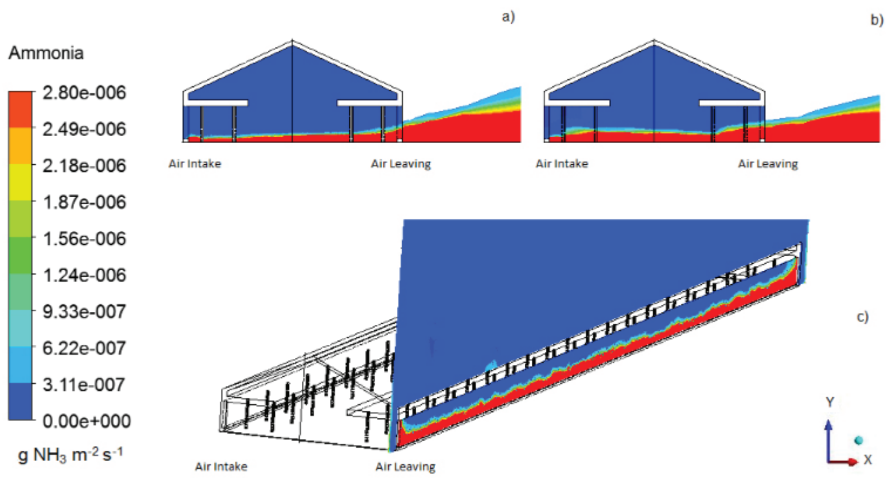

Figure 7. Typical distribution of ammonia flux inside and outside of the opening poultry house: (a) effect with pillars; (b) effect without pillars at the center of the building; (c) plane at the lateral wall.

Despite the fact that the NH_3 flux data obtained for the naturally ventilated barn of this study were smaller as compared to other studies conducted in mechanically ventilated buildings, further studies are required to better explain the factors that lessens the emissions from naturally ventilated buildings. In any case, even being smaller, a more accurate quantification of the emissions from naturally ventilated buildings is needed due to the magnitude in number of this kind of installation in tropical and subtropical regions.

Limitations of the CFD model and suggestions for future work

Even though the CFD model developed to determine flow rate pattern, NH_3 concentration and flux profiles for the studied naturally ventilated building was well validated against the experimental data, there are some considerations that have to be taken into account for future work. (1) It would be interesting to improve the model by including varying wind speed and direction through the lateral entries of the building. (2) Another suggestion would be to test and use other turbulence models and analyze which one presents the best fit with the experimental data. (3) The effect of roughness generated by birds body surface on indoor airflow and (4) the effect of convective mass (water vapor) and metabolic heat released by the animals should also be considered.

CONCLUSIONS

The proposed CFD model presented a good statistical fit with the experimental data, and can be used to predict real time patterns of NH_3 concentration profiles and fluxes inside open broiler houses with incident winds in different velocities at the lateral opening. The most direct application of the proposed model is be to help improving the design of existing buildings and also to help in the conception of new ones. One may also apply the model to help in the development of NH_3 emission inventories.

The CFD model well represented the effect of NH_3 concentration near the outer walls and pillars at the exit of the installation. This outcome may be considered in the conception and design of new buildings, in which shorter outer walls height could be used to increase wind speed and consequently lessen NH_3 concentrations at the height of the birds. The proposed model allows the prediction of NH_3 concentration profiles and fluxes as a function of time when wind speed and the direction are set constant. However, in field conditions, these parameters vary significantly as a function of time. Therefore it is recommended to use maximum values of wind speed, temperature and NH_3 mass flux into the model, which are considered to be the most critical that can be encountered in real operation of the facilities for the purpose of designing new installations.

ACKNOWLEDGEMENTS

The authors thank the Brazilian government agencies: FAPEMIG (Foundation to Support of Research in the State of Minas Gerais), and CNPq (National Council of Technological and Scientific Development).

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